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Collisional disruption of planetesimals in the gravity regime with iSALE code: Comparison with SPH code for purely hydrodynamic bodies

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ABSTRACT

In most of the previous studies related to collisional disruption of planetesimals in the gravity regime, Smoothed Particle Hydrodynamics (SPH) simulations have been used. On the other hand, impact simulations using grid-based hydrodynamic code have not been sufficiently performed. In the present study, we execute impact simulations in the gravity regime using the shock-physics code iSALE, which is a grid-based Eulerian hydrocode. We examine the dependence of the critical specific impact energy Q^*_{RD} on impact conditions for a wide range of specific impact energy (Q_R) from disruptive collisions to erosive collisions, and compare our results with previous studies. We find that collision outcomes of the iSALE simulation agree well with those of the SPH simulation. Detailed analysis mainly gives three results. (1) The value of Q^*_{RD} depends on numerical resolution, and is close to convergence with increasing numerical resolution. The difference in converged value of Q^*_{RD} between the iSALE code and the SPH code is within 30%. (2) Ejected mass normalized by total mass (M_{ej}/M_{tot}) generally depends on various impact conditions. However, when Q_R is normalized by Q^*_{RD} that is calculated for each impact simulation, M_{ej}/M_{tot} can be scaled by Q_R/Q^*_{RD}, and is independent of numerical resolution, impact velocity and target size. (3) This similarity law for Q_R/Q^*_{RD} is confirmed for a wide range of specific impact energy. We also derive a semi-analytic formula for Q^*_{RD} based on the similarity law and the crater scaling law. We find that the semi-analytic formula for the case with a non-porous object is consistent with numerical results.

1. Introduction

Collisions are one of the most important processes in planet formation because planetary bodies in the Solar System are thought to have experienced a lot of collisions during the accretion process (e.g., Lissauer and formation, 1993). Thus, collisional processes have been examined extensively. Roughly speaking, collisional outcomes can be classified into disruptive collisions and erosive collisions by the specific impact energy Q_R, given by

$$Q_R = \left(\frac{1}{2}M_{tar}V_{tar}^2 + \frac{1}{2}M_{imp}V_{imp}^2\right)/M_{tot} = \left(\frac{1}{2}M_R v_{imp}^2\right)/M_{tot}, \quad (1)$$

where M_{tar} and M_{imp} are the mass of the target and the impactor ($M_{tar} > M_{imp}$, $M_{tot} = M_{tar} + M_{imp}$), respectively, and V_{tar} and V_{imp} are the velocities of the target and the impactor in the frame of the center of mass when the two objects contact each other, respectively, M_R is the reduced mass, given by $M_{imp}M_{tar}/M_{tot}$, and v_{imp} is the impact velocity ($v_{imp} = V_{imp} - V_{tar}$ for negative V_{tar}). In particular, the specific impact energy required to disperse the largest body such that it has exactly half its total mass after the collision is called the critical specific impact energy Q^*_{RD}. In the case of $Q_R > Q^*_{RD}$, collisions between planetesimals are regarded as disruptive collisions, while they are non-disruptive collisions for $Q_R \ll Q^*_{RD}$, whose mass ejection is small (hereafter called erosive collisions).

The values of Q^*_{RD} have been investigated by laboratory experiments and numerical simulations (e.g., Benz and Asphaug, 1999; Nakamura et al., 2009). When the target is small enough to neglect the effect of the target's gravity, the critical specific impact energy is mainly estimated by laboratory experiments (Housen and Holsapple, 1999; Nakamura et al., 2009). As target size increases, collision outcomes gradually become dominated by the gravity of the target. However, direct experimental measurements of a large scale collision are difficult to carry out in the laboratory. Thus, the values of Q^*_{RD} for large targets ($\gtrsim$1 km) are estimated via shock-physics code calculations, which compute the propagation of the shock wave caused by a high velocity collision ($\gtrsim$km/s): Lagrangian hydrocode such as Smoothed Particle Hydrodynamics (SPH) methods (Love and Ahrens, 1996; Melosh

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and Ryan, 1997; Benz and Asphaug, 1999; Jutzi et al., 2010; Genda et al., 2015; Jutzi, 2015; Movshovitz et al., 2016; Genda et al., 2017), or a hybrid code of Eulerian hydrocode and N-body (Leinhardt and Stewart, 2009). These numerical simulations showed the dependence of the value of $Q^*_{\rm RD}$ on various impact conditions such as target size, impact velocity, material properties, and impact angle. For example, the value of $Q^*_{\rm RD}$ in the gravity regime increases nearly monotonically with the size of the target because collisional fragments are more easily bound by the gravitational force of the target. The critical specific impact energy also depends on the material property (e.g. material strength, porosity, and friction) of the impactor and the target (Leinhardt and Stewart, 2009; Jutzi et al., 2010; Jutzi, 2015). Notably, the friction significantly dissipates impact energy (Kurosawa and Genda, 2018), which tends to hinder the disruption of the target. The value of $Q^*_{\rm RD}$ then reaches about 10 times the value of $Q^*_{\rm RD}$ without the friction (Jutzi, 2015). Moreover, recent impact simulations show that $Q^*_{\rm RD}$ depends not only on impact conditions, but also on numerical resolution (Genda et al., 2015; 2017). Genda et al. (2015) performed SPH simulation at various numerical resolutions, and showed that $Q^*_{\rm RD}$ at high numerical resolution is rather low compared to the case of low resolution.

In addition to the critical specific impact energy, the understanding of erosive collisions is also important in relation to the formation of planetary bodies. In most of the previous studies, the contribution of erosive collision to growth of the planets has been underestimated because the amount of mass ejected by erosive collision is much smaller than the total mass. However, some previous studies showed that erosive collision also plays an important role in planetary accretion (Kobayashi and Tanaka, 2010; Kobayashi et al., 2010; 2011). Kobayashi and Tanaka (2010) assumed a simple fragmentation model describing both disruptive collisions and erosive collisions, and investigated mass depletion time in a collision cascade based on analytic consideration and numerical simulation. They showed that erosive collisions occur much more frequently than disruptive collisions and the mass depletion time is mainly determined by erosive collisions. Recently, the validity of the simple fragmentation model was examined by Genda et al. (2017), who performed impact simulations for a wide range of specific impact energy using the SPH method with self-gravity and without material strength (i.e. a purely hydrodynamic case), and showed that the fragmentation model is consistent with collisional outcomes of simulations within a factor of two. They also showed that the ejected mass normalized by the total mass can be scaled by $Q_{\rm R}/Q^*_{\rm RD}$ for their parameter range.

However, almost all high velocity collisions have been examined by the SPH method. Another common hydrodynamic simulation, whose computational domain is discretized by grids, has also been carried out (e.g., Leinhardt and Stewart, 2009). However, the grid-based code is only used for the shock deformation immediately after collision, and a large part of the disruption is calculated by N-body simulation. Thus, impact simulation using the grid-based code has not been sufficiently performed, though it is important to examine the problem with a different numerical approach.

In this study, we perform impact simulations in the gravity regime by using shock-physics code iSALE (Amsden et al., 1980; Collins et al., 2004; 2016; Wünnemann et al., 2006), which is a grid-based Eulerian hydrocode, and has been widely distributed to academic users in the impact community. This code has been used to understand various impact phenomena: crater formation (Collins et al., 2008; Cremonese et al., 2012), impact jetting (Johnson et al., 2015; Wakita et al., 2017; Kurosawa et al., 2018), pairwise collisions of planetesimals with/without self-gravity (Davison et al., 2010; 2012) and comparison with experimental data (Nagaki et al., 2016; Kadono et al., 2018). We examine the dependence of $Q^*_{\rm RD}$ on numerical resolution and impact conditions for a wide range of specific impact energy from disruptive collisions to erosive collisions, and compare our results with previous studies. Furthermore, using numerical results obtained by the iSALE code and the crater scaling law, we derive a semi-analytic formula for $Q^*_{\rm RD}$.

In Section 2, we present methods for impact simulations and analysis. We show our numerical outcomes of simulations in the case of disruptive collisions in Section 3. In Section 4, we establish a similarity law for $Q_{\rm R}/Q^*_{\rm RD}$ for a wide range of impact energy, and derive a semi-analytic formula for $Q^*_{\rm RD}$. We discuss effects of oblique collisions and material properties in our results in Section 5. Section 6 summarizes our results.

2. Numerical methods

In this study, we examine collisions between planetesimals using shock-physics code iSALE-2D, the version of which is iSALE-Chicxulub. The iSALE-2D is an extension of the SALE hydrocode (Amsden et al., 1980). To simulate hypervelocity impact processes in solid materials, SALE was modified to include an elasto-plastic constitutive model, fragmentation models, and multiple materials (Melosh et al., 1992; Ivanov et al., 1997). More recent improvements include a modified strength model (Collins et al., 2004), and a porosity compaction model (Wünnemann et al., 2006; Collins et al., 2011).

The iSALE-2D supports two types of equation of state: ANEOS (Thompson and Lauson, 1972; Melosh, 2007) and Tillotson equation of state (Tillotson, 1962). These equations of state have been widely applied in previous studies including planet- and planetesimal-size collisional simulations (e.g. Canup and Asphaug, 2001; Canup, 2004; Fukuzaki et al., 2010; Ćuk and Stewart, 2012; Sekine and Genda, 2012; Hosono et al., 2016; Wakita et al., 2017). In our simulation, we use the Tillotson equation of state for basalt because almost all previous studies related to collisional disruption have used the Tillotson equation of state, which allows us to directly compare our results with theirs. The Tillotson equation of state contains ten material parameters, and the pressure is expressed as a function of the density and the specific internal energy; all of which are convenient when used in works regarding fluid dynamics. Although the Tillotson parameters for basalt of the iSALE-2D are set to experimental values, we used the parameter sets of basalt referenced in previous works (Benz and Asphaug, 1999; Genda et al., 2015; 2017).

We employ the two-dimensional cylindrical coordinate system and perform head-on impact simulations between two planetesimals (Fig. 1). We assumed that planetesimals are not differentiated. Planetesimals are also assumed to be composed of basalt. For nominal cases, the radius of the target $R_{\rm tar}$ and the impact velocity of the impactor $v_{\rm imp}$ are fixed at 100 km and 3 km/s, respectively. We also examine the dependence of collisional outcome on target size and impact velocity in Section 3.2. To carry out impact simulations with various impact energy $Q_{\rm R}$, we changed the radius of the impactor $R_{\rm imp}$. For example, $R_{\rm imp}$ = 14–21 km (i.e., $Q_{\rm R} \simeq$ 12–41 kJ/kg). In this study, we consider four cases with the number of cells per target radius ($n_{\rm tar}$ = 100, 200, 400, and 800). Then, the total number of numerical cells in the computational domain ($n_{\rm v} \times n_{\rm h}$, see Fig. 1) is changed depending on $n_{\rm tar}$. For example, $(n_{\rm v} \times n_{\rm h}) = (450 \times 450), (900 \times 900), (1800 \times 1800)$, and (3600×3600) at $n_{\rm tar}$ = 100, 200, 400, and 800, respectively. In the case of $R_{\rm tar}$ = 100 km, the values of the spatial cell size for each numerical resolution $\Delta x (=R_{\rm tar}/n_{\rm tar})$ are Δx = 1000, 500, 250, and 125 m, and the size of the computational domain is fixed at $(n_{\rm v}\Delta x,\ n_{\rm h}\Delta x)$=(450 km, 450 km).

The aim of this study is to make a direct comparison of collisional outcomes between different numerical codes (SPH code and iSALE code). Therefore, although the iSALE-2D can deal with the effects of material strength, damage, and porosity of the target and the impactor, these effects are not taken into account in the present work; that is, the fluid motion is purely hydrodynamic. The self-gravity is calculated by the algorithm in the iSALE-2D based on a Barnes-Hut type algorithm, which can reduce the computational cost of updating the gravity field. In most of our calculations, the opening angle θ, which is the ratio of mass length-scale to separation distance, is set to 1.0. Although the value of the opening angle is rather large, we confirmed that the